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Citation: Chin. Phys. B . 2018, 27(2): 027804. **doi:** 10.1088/1674-1056/27/2/027804

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TOPICAL REVIEW — Solid-state quantum information processing

Magneto–optical properties of self-assembled InAs quantum dots for quantum information processing*

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(Received 15 October 2017; revised manuscript received 3 November 2017; published online 29 January 2018)

Semiconductor quantum dots have been intensively investigated because of their fundamental role in solid-state quantum information processing. The energy levels of quantum dots are quantized and can be tuned by external field such as optical, electric, and magnetic field. In this review, we focus on the development of magneto–optical properties of single InAs quantum dots embedded in GaAs matrix, including charge injection, relaxation, tunneling, wavefunction distribution, and coupling between different dimensional materials. Finally, the perspective of coherent manipulation of quantum state of single self-assembled quantum dots by photocurrent spectroscopy with an applied magnetic field is discussed.

Keywords: magneto–photoluminescence, InAs quantum dots, quantum bit, wavefunction control, diamagnetic effects

PACS: 78.67.Hc, 78.55.Cr, 71.35.Ji **DOI:** 10.1088/1674-1056/27/2/027804

1. Introduction

Semiconductor quantum dots (QDs) have attracted considerable interest for applications in solid-state quantum information processing, such as quantum light sources,[1–5] quantum logic gates,[6] and quantum bits.[7,8] Since the first observation of exciton Rabi oscillation in single QDs,[9] a series of advancements has been achieved via coherent control of optical, electric, and magnetic field.[7,10–15] Because of a long decoherence time of carrier spin at low temperature,[15,16] and the easy coherent manipulation of charges, single spins and charges in single QDs are of great importance for investigating the relevant functional devices.

Magneto–photoluminescence spectroscopy is a promising tool to investigate the quantized degeneracy energy levels with opposite spins and the confinement of charge carriers in single QDs and surrounding materials. Magnetic-field effects are therefore expected to coherently manipulate the spin states,[17,18] the charge injection,[19,20] wavefunction distribution of QDs,[21,22] and coupling between different dimensional materials.[23–25] In this review, the basic properties of single self-assemble QDs and the influence of magnetic field effects on their optical properties of single self-assemble QDs are first introduced, then improvements on magneto–optical properties of single QDs containing the coherent manipulation of spin or charge states, wavefunction distribution and coupling to a continuum state are presented and finally photocurrent spectroscopy with applied magnetic field is discussed for possible implementation in future quantum computing.

2. Basics of QDs

Semiconductor QDs are quasi-zero-dimensional nanocrystals, with electrons and holes confined in all three dimensions. Quantum confinement leads to discrete energy states, which are similar to those of atoms, so QDs are often referred as 'artificial' atoms. The discrete energy level structure is closely related to the shape, size, surrounding materials, and external fields of the QDs. To avoid the deterioration of optical properties of the QDs caused by surface oxidation and defects, the QDs are embedded in GaAs matrix. Due to the advantages of sharp linewidth, long decoherence time of single spins, and compatibility of traditional semiconductor technology, single QDs are good candidates to manipulate quantum states coherently for possible applications in solid-state quantum information processing.

2.1. Exciton states

In semiconductor QDs, when the lowest energy level is occupied by a pair of electron and hole, the large Coulomb energies induced by strong carrier confinement leads to the bounded neutral exciton state. However, for most of the QDs, the magnitudes of Coulomb energies are comparable with the quantization energies,[26] leading to multiple charged excitons and biexcitons when extra electrons and holes are located in

*Project supported by the National Basic Research Program of China (Grant No. 2014CB921003), the National Natural Science Foundation of China (Grant Nos. 11721404, 51761145104, and 61675228), the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant Nos. XDB07030200 and XDPB0803), and the CAS Interdisciplinary Innovation Team.

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the QD. Due to Pauli exclusion principle, every discrete level in the QD allows no more than two carriers with opposite spin states to occupy, giving rise to biexciton, and multiple charged excitons with high excitation power as shown in Fig. 1. Different exciton states in a single self-assembled InGaAs QD have been investigated by photoluminescence (PL) technique.[20,26]

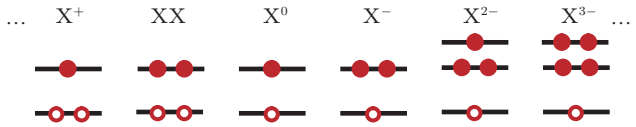


Fig. 1. Schematic diagrams of neutral exciton, biexciton, and multiple charged excitons. Dots and circles represent electrons and holes, respectively.

To achieve different excitons in single QDs with single electron charging, p–i–n junction or Schottky device is fabricated to control the electronic properties.[20,27–32] Up to now, the charging from +6e to −6e with precision of single elementary charge in a single QD has been demonstrated using PL spectroscopy.[31] As shown in Fig. 2(a),[20] with an applied electric field, the exciton states can be tuned from X^{3-} to X^{+} precisely. In a Schottky diode structure with band profiles as illustrated in Fig. 2(b), the energy band is tuned with an external bias to control the charging of the QDs. With a negative bias voltage, electrons are more easily to tunnel out of the QDs, while for positive bias more electrons are localized in QDs. Therefore, with bias voltage increasing from negative to positive, the QDs are more negatively charged, resulting in relatively stronger PL intensities of the negatively charged excitons. The charge states can also be modulated precisely by magnetic field, which will be introduced in Subsection 4.1.

For neutral excitons which consist of one electron and hole pair in the QDs, due to the asymmetry of the QDs, a fine structure splitting with energy of about dozens of μeV[33] is generated by electron–hole exchange interaction of an exciton. The fine structure splitting changes the polarization of the excitons from circular to linear polarization, which plays an important role in controlling the charge and spin states in QDs. The fine structure splitting can be eliminated by external fields such as magnetic field,[34,35] electric field,[36,37] and strain,[38] etc., to achieve entangled photon pairs, or high-fidelity initialization of spins to implement solid state quantum information processing.

Excitonic qubits are superposition of ground state and exciton state of a two-level system. The dephasing times for excitons at low temperature in self-assembled QDs typically are several hundred picoseconds, allowing a coherent manipulation to realize Rabi oscillation,[9,10,39] C-ROT gate,[6] and so on. For spin qubits, some significant progresses have been made due to the long decoherence time for spins of electrons and holes which are decoupled well from the orbital or charge degrees of freedom at low-temperature in single QDs, more details are shown in Subsection 4.1.

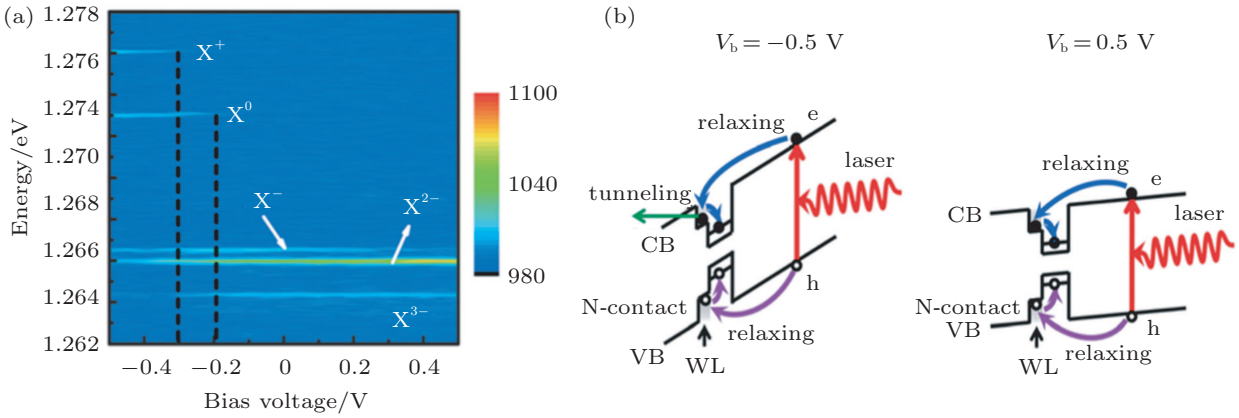


Fig. 2. (color online) (a) PL spectra with bias voltages sweeping from −0.5 V to +0.5 V of a single QD embedded in an n–i–Schottky device with an excitation power of 2.37 μW. The PL peaks from X^{3-}, X^{2-}, X^{-}, X^{0}, and X^{+} are labeled in the figure. The dotted lines mark the beginning of emission lines of X^{0} and X^{+}. (b) Band profiles of the n–i–Schottky diode structure under bias voltages of −0.5 V and +0.5 V. The energy bands tilt with the two bias voltages due to the built-in electric field of the structure. A positive bias voltage of 0.75 V calculated by one-dimensional Poisson–Schrödiner solver and measured via the photocurrent signal is required to achieve zero total electric field in this structure. With non-resonant excitation, the photo-generated carriers first emerge at GaAs matrix, then relax to wetting layer, finally are captured by QDs, as marked by blue and purple arrows.[20]

2.2. Photoluminescence of single QDs

PL spectrum is an important experimental technique to investigate the optical properties of semiconductor InAs QDs embedded in GaAs matrix, which is usually measured at low temperature to eliminate the thermal effect. In this review, most of the experiment are performed with non-resonant excitation, for which the energy of the laser is higher than the energy of QDs. With non-resonant excitation, the photo-generated carriers first emerge at GaAs matrix, then relax to the lowest energy level of the QDs. After recombination of bounded electron and hole pair, a photon is emitted with a typical radiative lifetime of hundreds of picoseconds,[40] resulting in discrete and very narrow lines in the emission spectra.

The optical properties of single QDs are directly related to the charge injection, relaxation, tunneling, transport of charge carriers at GaAs matrix, and the interactions be-

tween carriers captured by QDs or wetting layers. In addition, these properties are sensitive to external parameters such as temperature,[41] strain,[42] electric field,[17,20,43,44] and magnetic field,[19,22,45] etc. Therefore, the PL spectra with applied external fields are investigated intensively to control and manipulate single spins or charges in single QDs.

3. Magnetic field effects on the optical properties of single QDs

Magneto-PL is a powerful tool to characterize the electronic and structural parameters of quantized energy level of single QDs. In the presence of a magnetic field applied along the growth direction, the charge carriers in the QDs under an extra confinement in lateral plane induced by cyclotron motion in the plane perpendicular to the magnetic field (Faraday geometry),[46] with a cyclotron frequency $\omega_c = eBm^*$, where e is the elementary charge, B is magnetic field, and m^* is the effective mass of charge carriers. Then the confinement by magnetic field is given by magnetic length (gyro-radius) $l_e = \sqrt{\hbar/eB}$, where $\hbar$ is the planck constant. The magnetic length is comparable to lateral size of QDs in a weak magnetic field, leading to a negligible confinement energy to the charge carriers in the QDs which can be reflected by diamagnetic shift and Zeeman effect.

3.1. Diamagnetic shift

The orbital motion couples to the magnetic field inducing the diamagnetic shift which reflects the confinement and Coulomb interaction determining the optical properties.[47] Diamagnetic shift reflects both the spatial confinements of QDs and interparticle Coulomb interactions under a magnetic field. Considering a single QDs as a model of harmonic oscillator, the quantized energy level of single QDs in the presence of a weak magnetic field applied along the growth direction is given by:

$$E_{l,m,n} = (2l+1+|m|)\hbar\sqrt{\frac{\omega_c^2}{4}+\omega_{xy}^2}+\frac{m}{2}\hbar\omega_c + \left(n+\frac{1}{2}\hbar\omega_z\right), \quad (1)$$

where l, m are angular momentum quantum number and magnetic quantum number, respectively. ω_{xy}, ω_z are oscillation frequency of the lateral plane and the growth direction of QDs, respectively. The ground state energy of the QDs in a weak magnetic field can be written as:

$$\begin{aligned} E_{0,0,0}(B) &= \hbar\sqrt{\frac{\omega_c^2}{4}+\omega_{xy}^2}+\frac{m}{2}\hbar\omega_c+\frac{1}{2}\hbar\omega_z \\ &= E_{0,0,0}(0)+\frac{1}{8}\frac{\hbar^2\omega_c^2}{E_{0,0}(0)} \\ &= E_{0,0,0}(0)+\gamma B^2, \end{aligned} \quad (2)$$

where $E_{0,0,0}(0)$ and $E_{0,0}(0)$ are ground state energy of the QDs and the confinement energy of the lateral plane respectively, γ is diamagnetic coefficient. It can be deduced from Eq. (2) that the diamagnetic coefficient is inversely proportional to the confinement energy of the lateral plane. The diamagnetic coefficient increases with an increasing QD diameter, which has been observed experimentally and theoretically,[47,48] with a typical value of 5 μeV/T^2–10 μeV/T^2.[20,21]

In a weak confinement regime, the interparticle Coulomb energies are equal to or dominate over the confinement energies of the QD, and the diamagnetic coefficient is proportional to the difference of wavefunctions of initial and final states.[49] Anomalous negative diamagnetic shifts for negatively charged excitons have been observed in small QDs with weak confinement where the electron wave function extended much into the barrier region,[23,50] as shown in Fig. 3. Such anomalous behaviors arise from the electron wave function extent after photon emission due to the absence of holes in the QD to attract electrons in its final state.

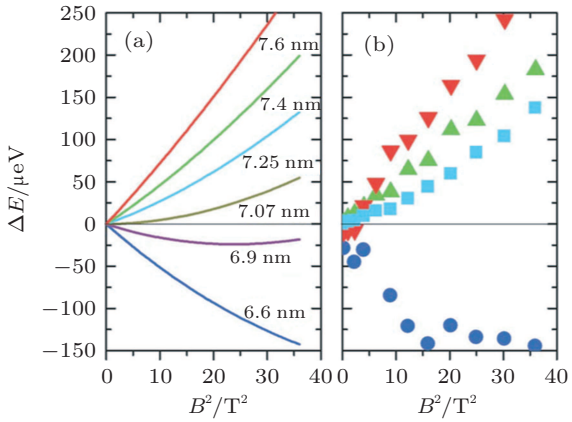


Fig. 3. (color online) The theoretical (a) and experimental (b) diamagnetic shifts with various diameters of single QDs.[50]

3.2. Zeeman effect

The spin of electron coupled to the magnetic field induces Zeeman splitting between spin up and spin down electron, which is studied intensively for their important applications in spintronics. The Zeeman splitting energy is presents as $\Delta E_{Zeeman} = g_{ex}\mu_B B$, where g_{ex} is the landé g factor of an exciton, μ_B is Bohr magneton. In Faraday geometry, the g factor is an important parameter for spin control and is strongly dependent on the height of the QDs.[51] The exciton g factor g_{ex} can be obtained in single QDs by measuring the energy splitting between the corresponding two circularly polarized lines with the relation:

$$g_{ex} = \frac{\Delta E_{Zeeman}}{\mu_B B} = \frac{E(\sigma^+)-E(\sigma^-)}{\mu_B B}, \quad (3)$$

which gives the g factors of excitons in a single QDs. The typical g factors for excitons in InAs/GaAs QDs are about 2.5–3.0.[20,21] In addition, the g factors of electrons and

holes separately can also be obtained by observing the dark excitons,[52] or achieved by pump-probe Faraday rotation spectroscopy.[53,54] To understand Zeeman effect on excitons of single QDs is important for manipulating the carrier spins.

4. Magneto–optical properties of single QDs

4.1. Coherent control of single spin or exciton states

Coherent control of single qubits is fundamental element for quantum algorithm, due to a long decoherence time up to microsecond of single electron or hole spins in QDs,[15,16] and the easy coherent manipulation of excitons,[55] single spin or exciton states in single semiconductor QDs are promising quantum qubits to implement quantum computing. Since Loss and DiVincenzo[56] in 1998 first proposed that single spins in semiconductor QDs can serve as a qubit, there are a series of important experimental and theoretical progresses have been achieved to manipulate single quantum qubit. Subsequently, Stievater,[9] Kamada,[10] *et al.* observed the Rabi oscillation of exciton in single InGaAs QDs, which were breakthrough works of QDs for implementing quantum computing.

The two basis states of carrier spin to act as qubits are spin up $|\uparrow\rangle$ state and spin down $|\downarrow\rangle$ state, which correspond to the classical bits "0" and "1". Quantum bits can be in superposition of the states $|\psi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle$, with $\alpha^2 + \beta^2 = 1$, which will greatly enhance the operational speed of computers greatly. A series of techniques are used to control the single electron spins in QDs such as ultrafast optical pulses,[12,57–66] optical cooling,[67] photocurrent,[7,11,15] quantum state transfer,[68] and external fields.[17,18,43,69,70]

Comparing with electron spins, hole spins have also been used to demonstrate spin qubits due to the p orbital property leading to a weaker hyperfine interaction with the nuclear spins,[8,71] and a longer decoherence time in microsecond regime.[72,73] Ultrafast high-fidelity initialization of a single quantum-dot hole spin was realized by controlling the relative electron and hole tunneling rates.[8] The initialization and measurement of fidelity scheme as shown in Fig. 4(a). The first σ^+ (σ^-) circularly polarized laser was used to achieve transition from ground state $|0\rangle$ to X^0 state $|\Uparrow,\downarrow\rangle$, ($|\Downarrow,\uparrow\rangle$) resonantly, due to the smaller effective mass of electron, the initialization of $|\Uparrow\rangle$ ($|\Downarrow\rangle$) state was realized through tunneling of electron controlled by an external electric field at a rate Γ_e (blue wavy arrows), then the second circularly polarized laser resonance with X^+ transition was applied to measure the fidelity of $|\Uparrow\rangle$ ($|\Downarrow\rangle$) initialization by comparing the polarization relative to the first laser. The initialization of hole spin fidelities can reach to 97.1% on a picosecond time scale. However, owning to the fine-structure splitting of single QDs, the coupling of two X^0 states at a frequency μ_{FS}/h (green double arrows in Fig. 4(a)) will lead to a loss in initialization fidelity of hole spin. The enhanced fidelity initialization of QD hole spin by reducing fine structure splitting has been achieved via an applied lateral magnetic field,[74] optical Stark effect,[75] and external electric field.[37,76] In the fast electron tunneling regime, the fine-structure splitting was almost eliminated by a vertical electric field to improve the hole spin fidelities as shown in Fig. 4(b).[37] Ultrafast initialization of individual hole spin qubits with near-unity fidelity is an important step to implement future quantum computing.

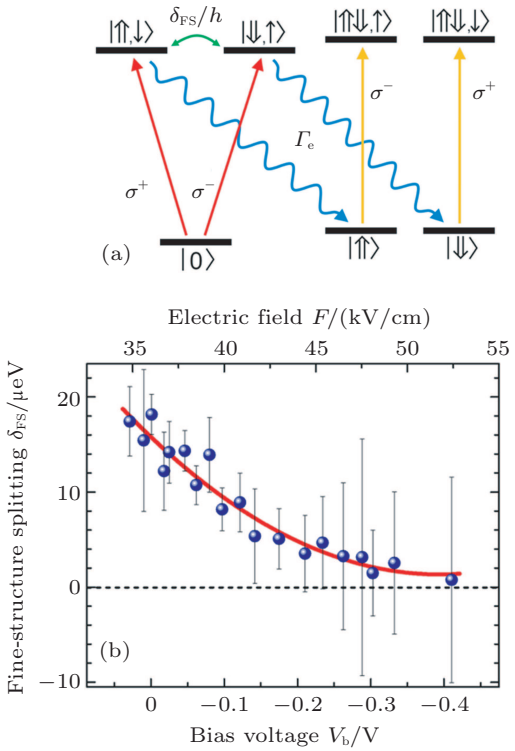


Fig. 4. (color online) Initialization and measurement of fidelity scheme for a single hole (a),[8] electric controlling of neutral exciton fine-structure splitting in a single QD (b).[37]

To achieve single charge or spin states, it is demanded to control the charge state of single QDs in precise way. Charge carriers in single QDs are generated by optical or electrical pumping.[2,77] Controlling the charge states depends on intentionally designed device structure,[78] doping semiconductor materials with n-type or p-type impurities,[53,79] external electric and/or magnetic fields.[19,26,80,81] Usually a delta-doped layer with a required charge density grown below the QD layer as n-type region and a semitransparent top contact was fabricated to connect external circuit.[20,82,83] For an n–i–Schottky device, the charge states of QDs have been controlled precisely by external bias.[27–29] The single QD charging from +6e to −6e with precision of single elementary charge due to Coulomb blockade has been realized using PL spectroscopy.[31]

Magneto-PL spectroscopy is a powerful tool to investigate the properties of different charge states in single QDs.[84,85] With non-resonant excitation, the charge carriers first generate at GaAs matrix in pairs, then relax to the wetting

layer and finally being captured by single QDs. Redistribution between different exciton states of a single QD has been observed with increasing magnetic field along the growth direction (Faraday geometry).[19] For a charge tunable device with sandwiched QDs as shown in Fig. 5(a), an external magnetic field along the growth direction of QDs (Faraday geometry) will affect in-plane transport of charge carriers due to cyclotron motion,[20] which will reduce their drift velocities. As shown in Fig. 5(b), with the increase of an applied magnetic field, the intensity of X^{3-} almost quenches at 6 T, the intensity of X^{2} decreases, while that of X^{-} increases, and intensities of X^{0} and X^{+} decrease slightly, which are more clear in Figs. 5(c) and 5(d). Owing to that the effective mass of heavy hole is larger than that of electrons,[86] holes are more easily being trapped by the localized potentials formed at the InAs/GaAs interfaces[87–89] than electrons, leading to that the intensity of higher negatively charged exciton peaks are getting weaker with increasing magnetic field, while the magnetic field is not high enough to modify the intensity of X^{0} and X^{+} peaks. The results indicate that the charging states of a single QD can be controlled by external magnetic field, which shows the promising implement to solid quantum information processing.

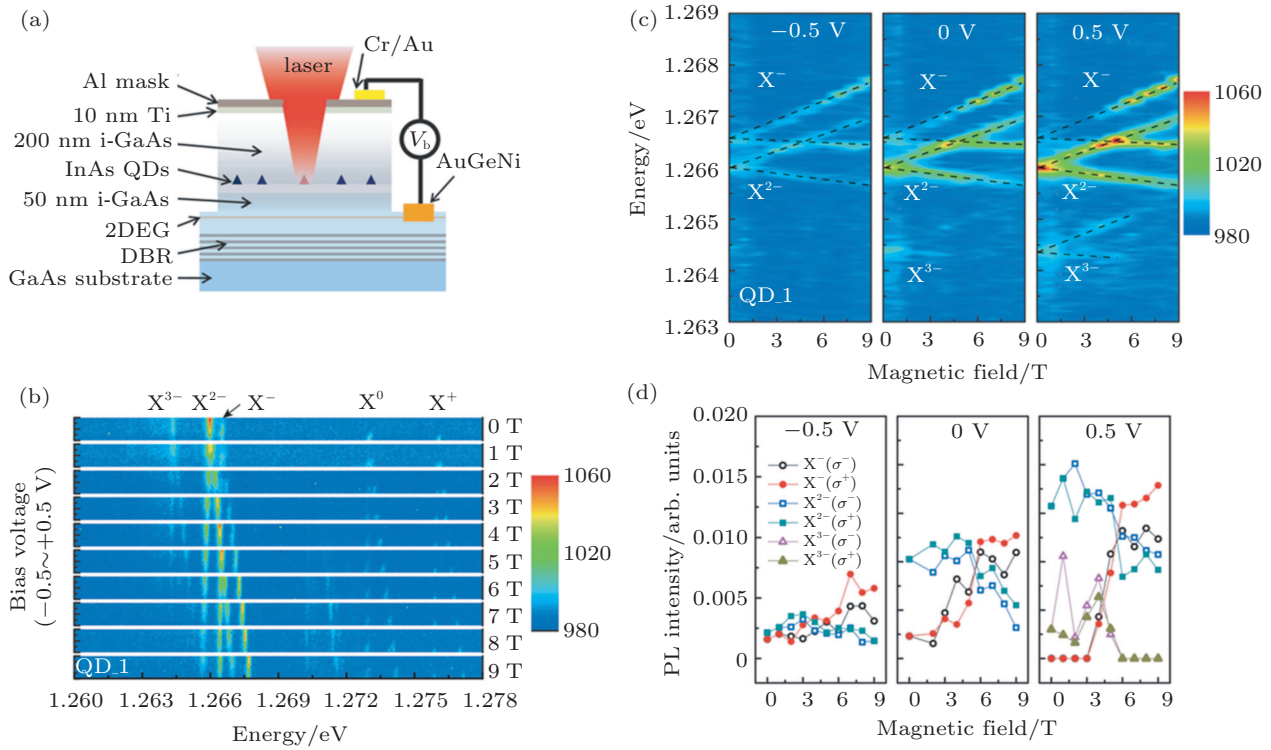


Fig. 5. (color online) A schematic diagram of an n–i–Schottky device. (b) Contour plot of the PL spectra of a single QD as a function of bias voltage from −0.5 V to +0.5 V with different magnetic fields from 0 T to 9 T in Faraday geometry. (c) PL spectra of X^{-}, X^{2-}, and X^{3-} as a function of applied magnetic field from 0 T to 9 T with bias voltage at −0.5 V, 0 V, and +0.5 V, respectively. (d) The integrated intensities of X^{-}, X^{2-}, and X^{3-} as a function of the applied magnetic field with different bias voltages.[20]

4.2. Longitudinal wave function control

Besides the modulation effect of charging states for single QDs, the applied magnetic field can also compressed the particles' wave functions because of the cyclotron motion. For implementing quantum information processing, it is important to investigate interactions between charge carriers in single QDs. The interactions depend on the overlapping between wavefunctions of electrons and holes, which are sensitive to external forces such as electric field or magnetic field. Wave function mapping has been demonstrated to investigate the interactions between electron states in quantum well or single QDs by scanning tunneling spectroscopy,[90,91] magnetocapacitance–voltage spectroscopy,[92–94] and magnetotunneling spectroscopy.[45,95–97]

For self-assemble QDs grown by molecular beam epitaxy, due to the asymmetry of shape and chemical composition variation along the growth direction, the center of effective mass of hole wave functions are separated from that of electron wave functions, leading to a permanent dipole moment even in the absence of electric field, which provides a good platform to investigate the charge wave function longitudinally controlled by external magnetic field. Due to the larger effective mass of hole and linearly increasing confined potential, the value of permanent dipole moment for pure InAs QDs with a pyramidal or truncated pyramidal shape are positive in direction from base to apex of the dot, which can be obtained by measuring the quantum-confined Stark effect with the relation[98–100]

$$E(F) = E(0) + pF + \beta F^{2}, \tag{4}$$

where $E(0)$ is the exciton transition energy at zero electric field, p is permanent dipole moment of single QDs, and β is polarizability.

The electron–hole alignment has been demonstrated experimentally and theoretically[98,101] and an inverted electron–hole alignment has been observed experimentally with Ga diffusing.[102] Once the growth process is completed, the permanent dipole moment is determined. However, the permanent dipole moment can be controlled by perpendicular magnetic field as shown in Fig. 6(a), the Stark shifts shift to opposite directions with the increase of magnetic field.[22] The permanent dipole moment as a function of magnetic field is shown in Fig. 6(b), revealing an inverting permanent dipole controlled by magnetic field, the polarizability (Fig. 6(c)) is much smaller than other results, indicating a flat QDs, so that the electron-hole alignment is more sensitive to the magnetic field, which is very useful to understand the quantum physics of single QDs.

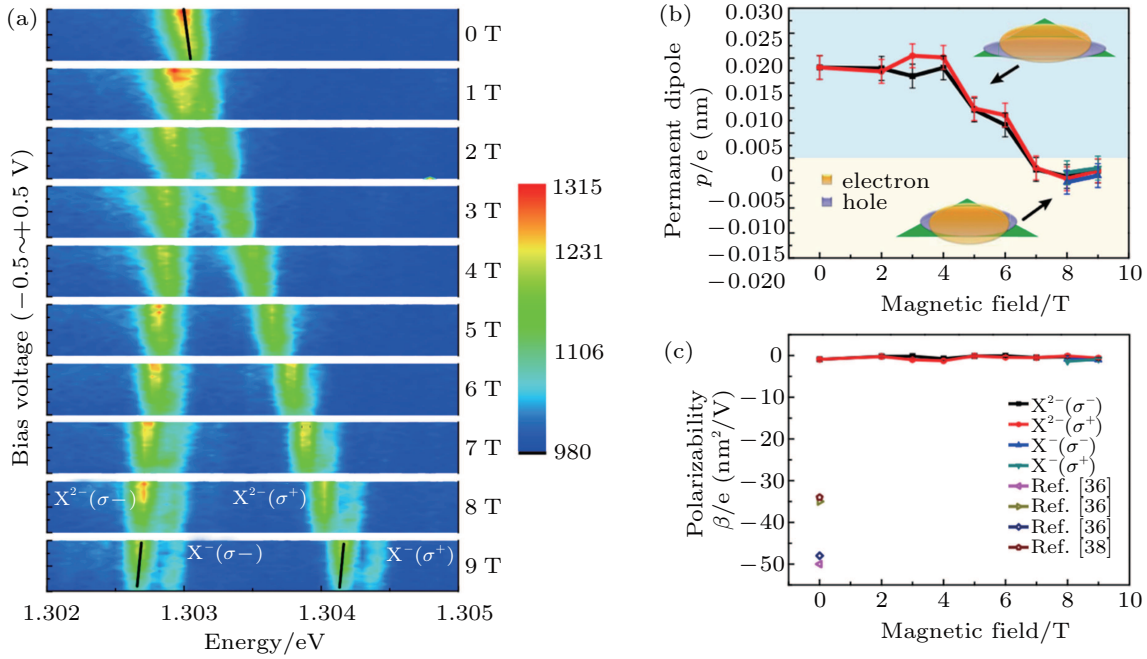


Fig. 6. (color online) (a) The contour plots of PL spectra of X^- and X^{2-} as a function of bias voltage from −0.5 V to +0.5 V at different magnetic fields. The solid black lines are marked to guide eyes for the Stark shifts. (b) The permanent dipole as a function of magnetic field. With increasing of magnetic field, the sign of dipole moment changes from positive to negative. Inset are schematic diagrams for electron/hole wave functions with smaller and higher magnetic field, respectively. (c) The polarizability of X^- and X^{2-} as a function of magnetic field. The empty symbols are data from Ref. [100] and *Phys. Rev. B* **70** 201308 (2004) for comparison.[22]

4.3. QDs coupled to a continuum state

Localized electrons coupling with the continuum of extended states has been investigated intensively in solid-state physics to understand Fano effect[103,104] and Kondo physics.[24,105–109] Self-assembled QDs grown by molecular beam epitaxy offer a platform to study many-body states by coupling with a wetting layer located underneath the QDs naturally[110–112] or Fermi sea in the back contact of the charging tunable devices.[24,106,113]

For QDs coupled to the back contact, many-body exciton states contain Mahan and hybrid excitons have been observed in a semiconductor QD interacting with a degenerate electron gas strongly.[106] The mechanisms for the two excitons states are different. Mahan excitons originate from the Coulomb interaction of the hole(s) confined in the QD and electrons in the Fermi sea controlled by gate voltages. However, the hybrid excitons are generated by the tunnel interaction of electrons between the continuum of states in the Fermi sea and confined state in the QD. The tunnel coupling will form Kondo excitons at low temperatures, which paves the way to study Kondo effect and voltage-control spin flips of electrons[113] in QDs.

For QDs coupled to the wetting layer with only several monolayers, coherent hybridization of localized QD states and continuum states of the wetting layer are demonstrated.[24,25] In the presence of magnetic field, the triply negatively charged exciton states X^{3-} in the QD has a remarkable series of anti-crossings in higher magnetic field, which is very different from other excitons with normal Zeeman effect and diamagnetic shift. The hybridization is generated as shown in Fig. 7. In a magnetic field along the growth direction of the QD, the two degenerated p-shell splits into two subshells, due to the spin-flip, the open shell state changes to a closed shell. After the recombination of the closed shell X^{3-}, one p-shell electron is promoted to d-shell due to Auger processes, inducing a coupling to Landau levels caused by magnetic field in wetting layer continuum states, leading to Kondo-like effects in the emission.

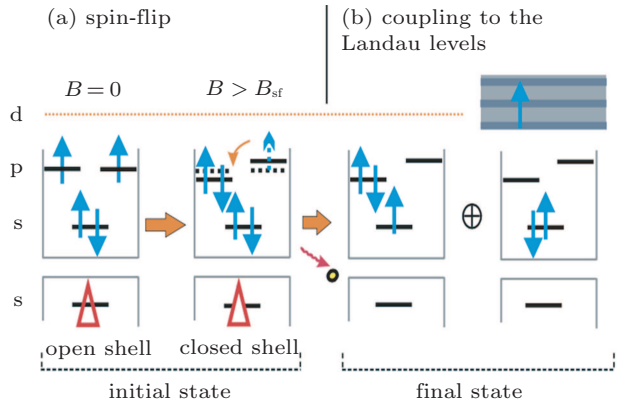


Fig. 7. (color online) (a) Configurations are shown for the initial of the triply charged exciton X^{3-} without and with a magnetic field, the spin-flip process leads to closed shell X^{3-}. (b) Hybridization in the final state after the recombination of closed shell X^{3-}, one p-shell electron is promoted to couple the Landau levels in wetting layer.[24]

In a weak magnetic field, diamagnetic shift of excitons reflects the spatial wavefunction distribution and Coulomb interactions in QDs.[47] Because of the different confined potential for charge carriers in quasi-zero-dimensional QDs and two-dimensional wetting layer, diamagnetic shift of excitons offers an effective way to study the coupling between quantum states with different dimensionalities. With a high excitation power in a magnetic field, peculiar diamagnetic shifts and anti-crossing generated by the coupling of X^{3-} and the wetting layer were observed as shown the right figure of Fig. 8(a).[23]

For strongly confined self-assembled InGaAs QDs, the diamagnetic coefficient is about 5 μeV/T^2–10 μeV/T^2,[20,50] however, tremendous 'positive' and 'negative' diamagnetic coefficients up to 93 μeV/T^2 and −51.7 μeV/T^2 are observed as shown in Figs. 8(a) and 8(b). The high values of diamagnetic coefficients imply greater wavefunctions expansion between the initial and final states for these exciton states. Since

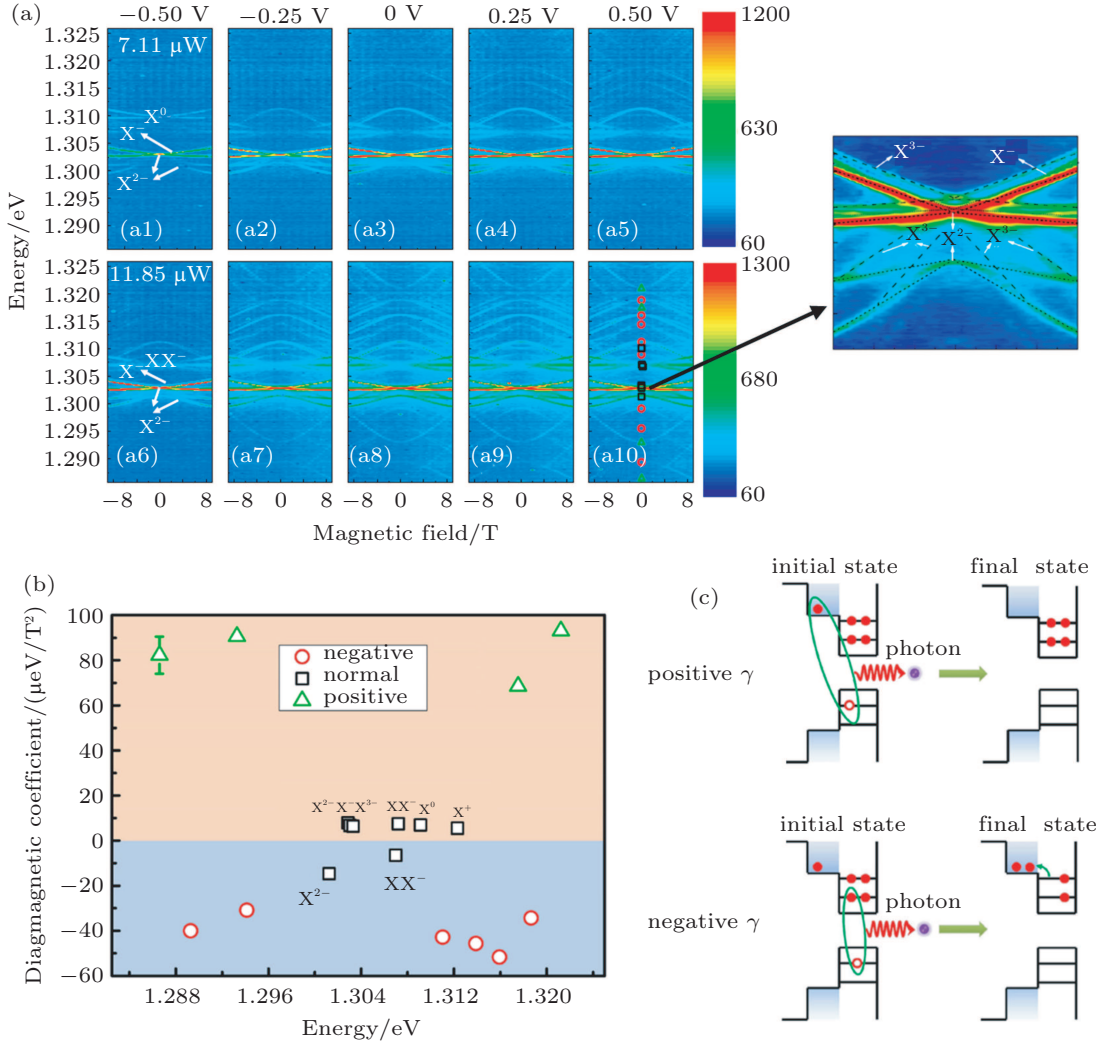


Fig. 8. (color online) (a) The contour plots of PL spectra as a function of magnetic field at different bias voltages with pumping power of 7.11 μW [(a1)–(a5)] and 11.85 μW [(a6)–(a10)]. With the increasing bias voltages and pumping power, additional weak peaks appear with strong diamagnetic shifts in the magnetic field. The peaks with normal, 'positive', and 'negative' diamagnetic coefficients are marked with black squares, green triangles, and red circlesas labeled on panel (a10). In addition, the right figure shows the enlarged anti-crossing of X^{3-} exciton. (b) The calculated diamagnetic coefficients of different charge states in a coupled system at a pumping power of 11.85 μW and a bias voltage of +0.5 V. (c) Schematic energy diagrams of the initial and final states of negatively charged exciton states in the coupled QD-wetting layer system. When the electrons in the wetting layer recombine with holes in the QD, resulting in large positive diamagnetic shifts, while when electrons in the QD recombine with the holes in the QD, owing to the absence of attraction of the holes in the QD after recombination, the electrons in the wetting layer spread in the final states and large wavefunction distribution differences between the initial and final states are formed, resulting in a negative diamagnetic effect.[23]

the holes are confined in the dot for the coupled QD-wetting layer system, there are two recombination paths for the anomalous PL peaks generated by many-body Mahan exciton states through Coulomb interaction as shown in Fig. 8(c).

With a high excitation power, optically generated electrons gradually occupy the higher energy level of QDs and the wetting layer. The large 'positive' diamagnetic coefficient close to that of bulk materials is observed for the recombination of electrons in the wetting layer with holes in QD because of the large wavefunction expansion in the wetting layer. While the large 'negative' diamagnetic effect is observed in the regime of weak confinement, corresponding to the recombination of electrons and holes in the QD when a huge difference of wavefunction extents between the initial and final states because of the absence of holes in the QD to attract electrons in the final states. The direct observation of hybrid states between a single QD and a wetting layer by strong diamagnetic shifts of many-body exciton states paves a new way to investigate the Kondo physics.

5. Conclusion and perspectives

In recent years, remarkable progresses have been achieved based on single semiconductor QDs to coherently manipulate quantum states by using magneto-PL spectroscopy. The external magnetic field is an effective technique to study the quantum physics in single QDs due to the cyclotron energy for carriers, Zeeman, and diamagnetic effects. With a magnetic field, the charge or spin states and wavefunctions of carriers can be controlled precisely. In addition, the coupling between single QDs and Fermi sea or wetting layer continuum states have been discussed by magneto-PL. These are important steps to achieve applications on solid state quantum computing and quantum information processing.

Photocurrent (PC) spectroscopy is a highly sensitive, quantitative technique to achieve spin/exciton qubits[7,8,14,71,74,114] by probing tunneling and relaxing information to manipulate quantum states, such as the realization of photocurrent readout of hole spin state[14] and dark exciton state.[115] By using the narrow bandwidth laser, the PC spectrum can have very narrow linewidth with a high-resolution.[116] With an applied magnetic field in Voigt geometry, the hole spin has coherent rotations by Larmor pression to achieve full controll experimentally[71] and theoretically.[114] In principle, an arbitrary phase shift on a single spin may be realized by a magnetic field applied in Voigt configuration,[117] which will have important applications in solid quantum computing and quantum information processing.

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